N 00014-93-1-0767

Final Report

Sensors for In-Situ and In-Process Measurements in Microelectronics Manufacturing

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This final report summarizes the progress we have made in developing ultrasonic sensors for in-situ monitoring of IC manufacturing processes. The work was done in collaboration with SRC funding.

We report a temperature measurement technique based on the temperature dependence of acoustic wave velocity in silicon wafers. The zeroth order antisymmetric Lamb wave is excited in the wafer using the quartz pins which support the wafer during processing. Extensional waves are generated in the quartz pin by a PZT-5H transducer and the acoustic energy is coupled to the Lamb wave at the contact between the sharpened end of the pin and the wafer surface. The detection is done by a similarly modified quartz pin or pins. By measuring the time of flight of the Lamb wave in the wafer between the two pins, we have monitored the wafer temperature in-situ in the 20 - 1000°C range with ±1 accuracy. Theoretical models considering wave propagation and thin film effects on the technique are developed for direct comparison with experimental results. With 8 spring loaded pins placed on a circular array around the wafer, 28 different measurements are made giving information about different regions. Using tomographic reconstruction techniques, spatial temperature distribution with 2 cm pixel size is then calculated. Excellent agreement is observed between the readings of thermocouples attached to the wafer, and calculated values for ultrasonic tomography. A method for temperature tomography with a smaller number of sensors is also proposed based on theoretical calculations.

INTRODUCTION

Temperature is a very critical parameter to be accurately monitored and controlled in semiconductor processing, since most processing steps are thermally activated [1]. Currently, optical pyrometers are the dominant temperature sensors in semiconductor industry. Their reading depends on the thermal radiation from the wafer which is very sensitive to wafer emissivity variations. Various factors such as film deposition, surface roughness and doping levels affect emissivity, making pyrometer readings inaccurate. Thermocouples are accurate to ±5°C, but they are not used in-situ, because of contamination at high temperatures and non uniformity problems. Thermal expansion measurements suffer from low sensitivity [2].

Acoustic waves are also sensitive to temperature, through the temperature dependence of elastic constants. For silicon, these sensitivity figures have been measured [3]. Using these figures we have calculated that, for antisymmetric Lamb waves, the group velocity has a temperature coefficient of -1.6 E-5 (1/°C), which is an order of magnitude larger than the thermal expansion coefficient.

For in-situ ultrasonic thermometry, we use the quartz support pins placed near the edge of the wafer to excite ultrasonic waves in the wafer. In particular, the zeroth order antisymmetric Lamb wave (A0 mode) is excited and the time of flight information is used to measure the wafer temperature. In the frequency range used, the wavelength is around

0.5 cm, making the technique virtually insensitive to other process parameters such as surface roughness. It is also non contacting in that there is no additional contact to the wafer other than the quartz support pins. Using ultrasonic thermometry, wafer temperature is monitored in-situ, in the 20 - 1000°C range with ±1°C accuracy. By increasing the number of transducer pins to 8, 28 measurements from different regions of the wafer are made, and the temperature distribution across the wafer is calculated, in-situ, using tomographic techniques.

PIN TO PIN TIME OF FLIGHT MEASUREMENT

In single wafer semiconductor processing chambers, the wafers are supported by quartz pins as depicted in Fig. 1. The low thermal conductivity of quartz prevents heat transfer from the wafer to the environment and maintains temperature uniformity in the wafer. These pins are used to couple acoustic energy to a Lamb wave mode in the wafer. The PZT-5H transducer bonded to the end of the quartz rod generates extensional waves with 40% fractional bandwidth around a center frequency of 200 KHz. The transducers are isolated from the high temperature and reactive gases in the process chamber by placing them in a nitrogen cooled, stainless steel housing. To have a well defined, repeatable point contact with the wafer, the contacting end of the quartz rod is sharpened and the tip is rounded to a radius of 100 μm.

Extensional waves are generated in the quartz rod by applying a 130 V negative electrical pulse at the PZT transducer terminals. This mode is coupled to the A0 mode in the wafer at the Hertzian contact formed at the quartz pin wafer interface. The Lamb wave propagates across the wafer. In a reverse process, an electrical signal is detected at the receiving transducer.

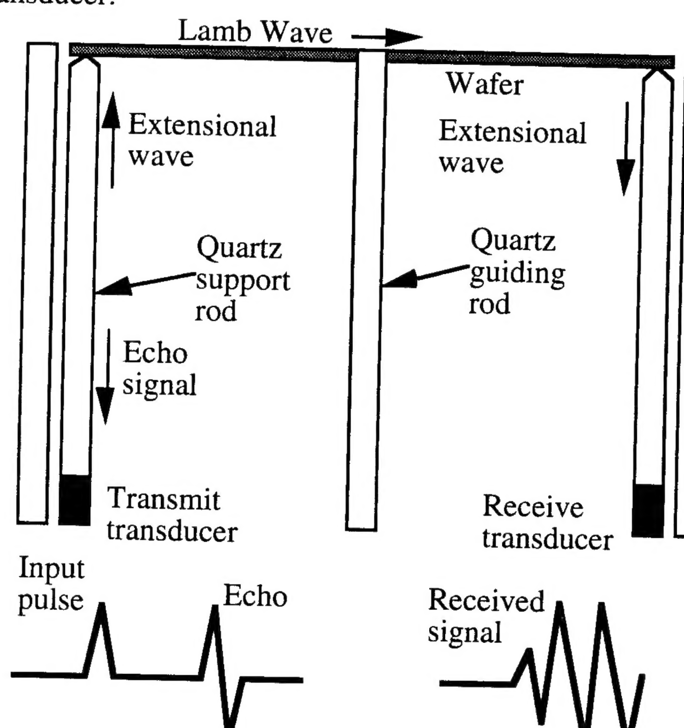

Figure 1. Pin to pin time of flight measurement setup.

The time of flight data is obtained by measuring the time delay between a zero crossing in the echo signal reflected from the tip of the transmit transducer and the

received signal at the other transducer. By using the zero crossing at the echo signal, the effect of temperature in the quartz pins is eliminated assuming that they are identical. In Fig. 2, the variation of pin to pin time of flight is plotted against the wafer temperature measured by a C-type thermocouple welded to the wafer. The sample is a 0.5 mm thick (100) silicon wafer with 10 cm diameter and the measurement is done in <100> direction. The wafer is heated by a 500 W tungsten halogen lamp. The time of flight is a very linear function of temperature and for this configuration, the sensitivity is 1.23 nsec/°C. The repetition rate is limited by the acoustic ringing in the wafer to 20 Hz, which is more than sufficient for temperature control applications.

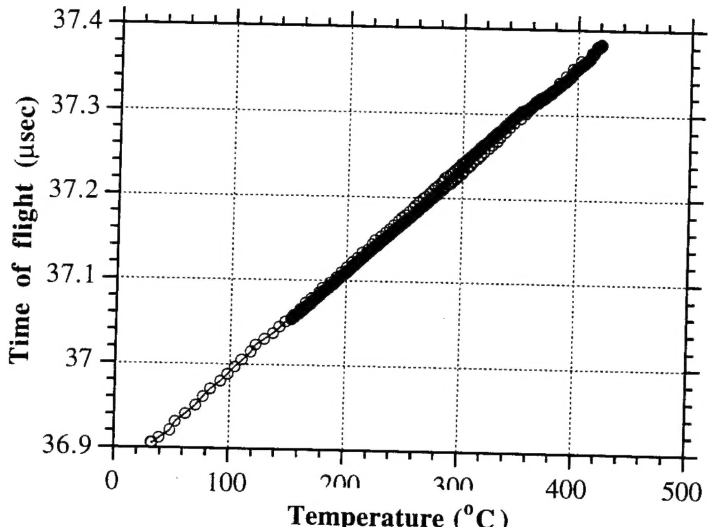

Figure 2. Measured time of flight as a function of wafer temperature.

The calculated temperature sensitivity figures for Lamb wave group and phase velocities do not provide precise quantities directly comparable to the experimental results. To make a direct comparison, the sensitivity of zero crossings of the received signal to temperature variations should be calculated. A theoretical model is developed for this purpose. In the model, the Hertzian contacts are treated as point sources and the propagation of Lamb waves is simulated considering diffraction and anisotropy of silicon. While calculating the resulting received waveform, the effect of the finite wafer geometry including the flats is also taken into account. This effect is important since the resulting waveform is a superposition of many waves reflected from the boundaries of the wafer and contains temperature information along their paths. In Fig. 3, the calculated received waveforms at T= 20°C and T= 500°C are depicted. The shift in time of flight with temperature is clearly seen. To investigate the time of flight variation for different zero crossings, 4 of of these are selected as indicated in the figure. The result of this calculation is plotted in Fig. 4. The variation of time of flight with temperature is linear for all zero crossings and the sensitivity is comparable to that of the experiments. Using this model, particular zero crossings can be chosen to selectively monitor temperature on different measurement paths with optimized pin locations.

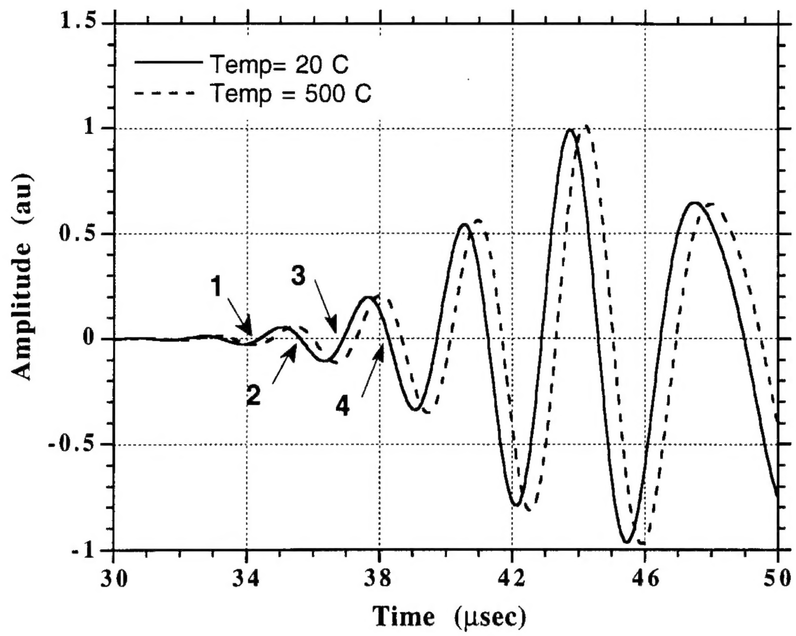

Figure 3. Calculated waveforms at the receiver for two different wafer temperatures. The arrows indicate the zero crossings used in Fig. 4.

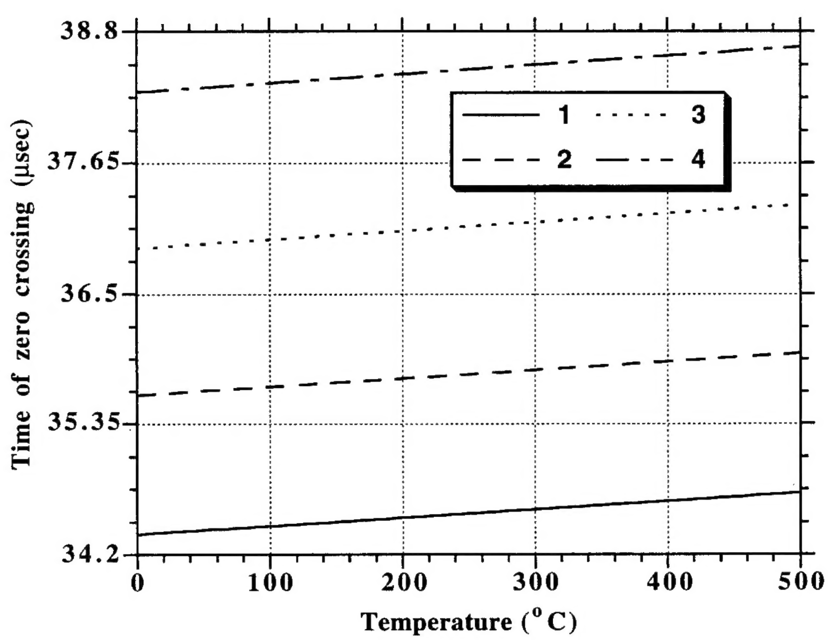

Figure 4. The variation of time of first 4 zero crossings with wafer temperature.

The accuracy of temperature measurement depends on the signal to noise ratio of the system. At constant temperature, the system is calibrated and the variation of temperature computed from the time of flight measurement is monitored as a function of signal to noise ratio. Fig. 5 shows the results of this experiment. By spring loading the pins, a larger Hertzian contact is made, and the system has a signal to noise ratio exceeding 50 dBs, which corresponds to a relative accuracy of better than ±1°C.

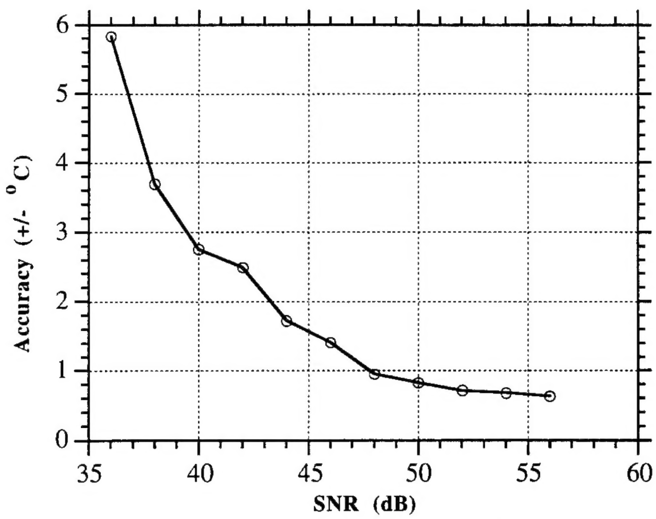

Figure 5. Relative temperature measurement accuracy of ultrasonic thermometry system as a function of SNR.

Ultrasonic thermometry is then used to measure wafer temperature in an actual semiconductor processor. The transducer pins and the housing are integrated in a Texas Instruments rapid thermal processor. To monitor temperature in-situ, during processing, a calibration run is made taking the thermocouple reading as reference at steady state levels. The data is then used to obtain a third order polynomial fit to relate time of flight to temperature. Fig. 6 shows the data obtained during an actual temperature transient in the rapid thermal processor. The thermocouple and ultrasonic thermometer results agree very well in the whole temperature range from room temperature up to 1000°C. The difference in the cooling interval results from the fact that the thermocouple reads the temperature at the center whereas the ultrasonic sensor gives the average wafer temperature. The heat loss is larger near the edge of the wafer resulting a smaller average temperature than the center.

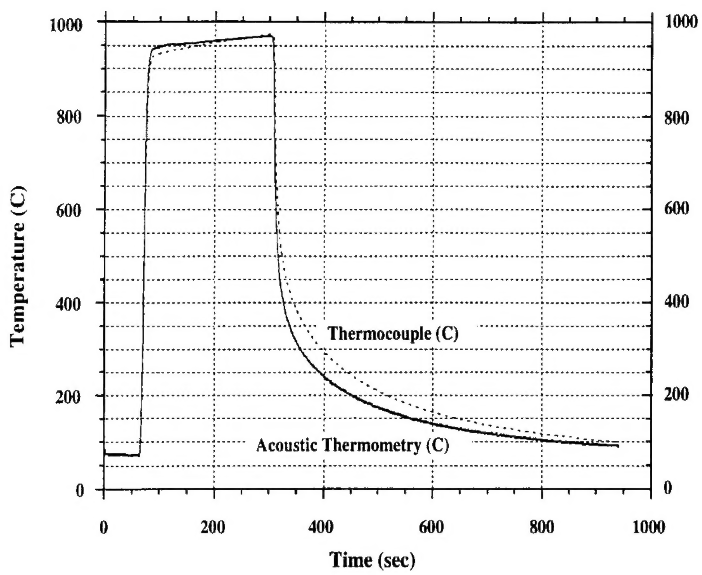

Figure 6. Actual temperature transient in rapid thermal processor as measured by ultrasonic thermometer and thermocouple.

During all processing steps in RTP, one or more thin films are either already present or deposited on the wafer. For accurate temperature measurement, the effect of thin films on Lamb waves should be considered. A theoretical model using the surface impedance concept is developed for this purpose [4]. The calculations show that the shear elastic constant and the density of the of the film material are the most critical factors. The effect of some thin films on phase velocity at room temperature equivalent to -1°C temperature change are tabulated in Table I. The results indicate that for less dense materials the velocity increases by deposition of films with increasing shear elastic constant, whereas for denser materials such as copper, the loading decreases the velocity resulting the sign reversal for the equivalent thickness.

-1°C Equivalent Film (Angstrom)	Aluminum	Silicon Oxide	Silicon Nitride	Copper
	704	472	185	- 337

Table I. The effect of thin films expressed as equivalent temperature change for 0.5 mm thick (100) silicon wafer.

The same modeling is also applied to examine the effect of thin films on temperature sensitivity. In the calculations, the films are assumed to be at the same temperature of the silicon wafer. For the film materials, the temperature coefficients found in literature are tabulated and used in the theoretical calculation [5]. In Figure 7, the temperature sensitivity of phase velocity as a function of film thickness is depicted for aluminum and silicon oxide films. As expected, the sensitivity increases for an aluminum film which has highly sensitive elastic constants, whereas for silicon oxide the effect is

reversed. It is also observed that for thin oxide films of the order of 100 Angstroms, the effect is negligible. Also, if there is an existing film on the wafer, the ultrasonic sensor can be calibrated using these curves. It should be noted that the calculations are done assuming a 0.5 mm thick 10 cm diameter silicon wafer and the effects of thin films are inversely proportional to wafer thickness. The developed model can also be used for multilayer films which are commonly used in semiconductor industry.

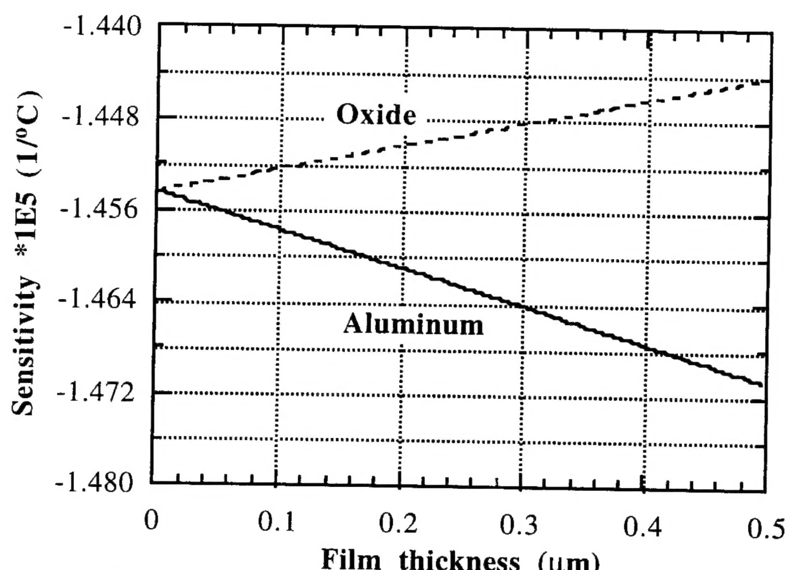

Figure 7. Temperature sensitivity of Lamb wave velocity variation with aluminum and oxide film thickness.

TEMPERATURE TOMOGRAPHY

The pin to pin time of flight measurement provides the average wafer temperature along the path connecting the two quartz pins. Of more importance is the temperature distribution on the wafer for temperature and process control applications. This information can be collected by measuring average temperature along many paths and inverting the data to get spatial distribution. Ultrasonic thermometry is used for this purpose and wafer temperature distribution is obtained by tomographic reconstruction.

Eight quartz pins are placed around the periphery of the silicon wafer as shown in Fig. 8. The pins are spring loaded to have repeatable contact with the wafer and better signal to noise ratio. With 8 pins, average temperature measurements along 28 different paths can be made as depicted in the same figure. The measurement procedure is the same as the two pin configuration. Using a computer controlled circuitry, the transducers are excited sequentially and time of flight data is collected from the other pins. Since all data acquisition is done sequentially, the data rate for an image is 1.4 sec. This figure can be reduced to 0.4 sec by using multiple time interval counters. For calibration, the wafer is brought to certain temperatures at steady state and the data for each path is stored. The acoustic anisotropy of silicon is eliminated by this calibration.

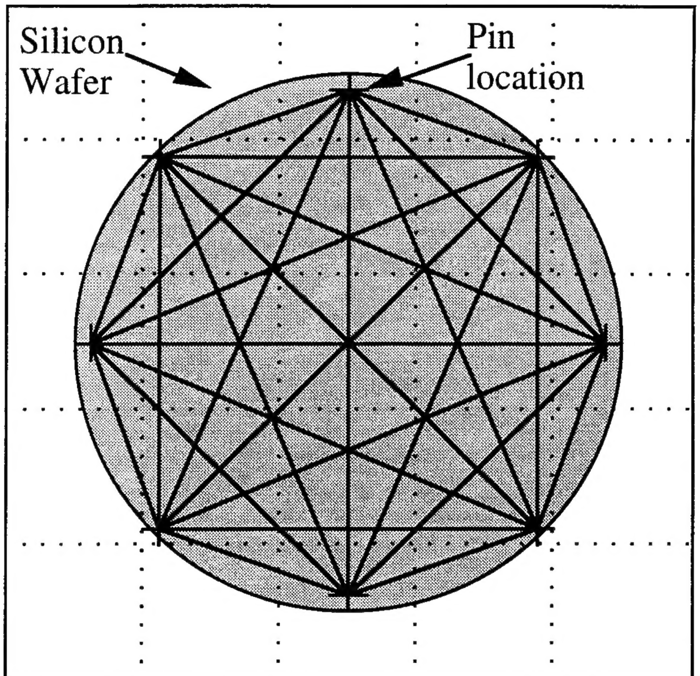

Figure 8. The pin locations and reference thermocouple joints used in temperature tomography. A possible rectangular pixel map is shown by the dashed lines.

For tomographic reconstruction the linear equation solving approach is used [6]. Two pixel maps are considered and corresponding projection matrices are calculated. To form the images, the time of flight data is converted to average temperature using the calibration function and the pixel values are calculated by a matrix multiplication. Since the maximum number of pixels is 28 the computation time is negligibly small as compared to data acquisition. Fig. 6 shows the reconstructed temperature distribution by ultrasonic thermometry along with the thermocouple reference values using circular pixels. This pixel map is convenient for semiconductor processors using circular heating lamp structure [7]. The circularly symmetric temperature distribution is obtained by masking the heating lamp properly. The agreement between the thermocouple readings and the acoustic tomography is excellent except the outermost ring, where the temperature gradient is large. Non symmetrical temperature profiles can be calculated with 2 cm pixel size by using a pixel map as in Fig. 5, by changing the projection matrix.

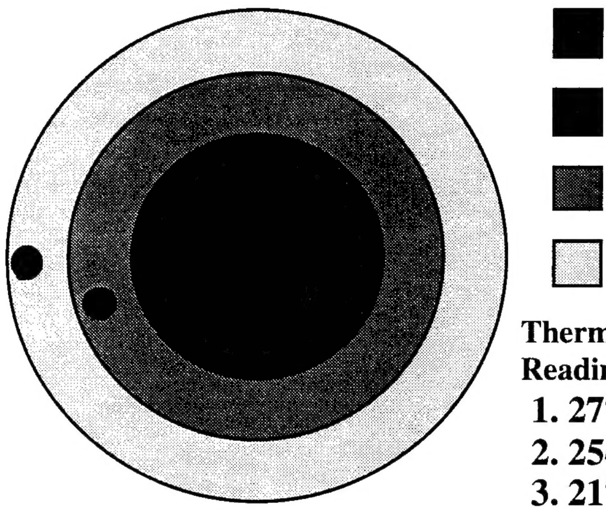

Figure 9. Calculated ultrasonic temperature tomography image of the silicon wafer with circular pixel map.

The resolution and accuracy of the temperature tomography system can be improved by increasing the number of measurement paths. Also, a priori information obtained from wafer heating simulations can be incorporated in reconstruction to minimize measurement errors.

In the method for temperature tomography described above only the first zero crossings are used to get average temperature along the direct path between the transmitter and receiver pins. However, different zero crossings of the received waveform carry information along different paths on the wafer. These paths result from the reflections from the edge of the wafer and can be computed easily by ray tracing. In Fig. 10, arrival times for the first 2 zero crossings of the received signal are plotted for two different temperature distributions on the wafer. In one case, the temperature is uniform across the wafer, whereas in the second case, there is a constant 50°C difference between the two halves of the wafer. The sensor pins are placed so that the direct path is on the uniform region close to the nonuniform region boundary. This unrealistic configuration had to be assumed for better illustration of principle. The calculations show that the first zero crossing variation is the same for both cases, since the nonuniformity has no affect on the direct path. However, starting with the second zero crossing, the waves traversing different paths across the nonuniform regions begin affecting the received signal. As a result, the variation of second zero crossing with temperature changes significantly. The effect on later arriving zero crossings is larger. Analyzing the contributions of different propagation paths to the received signal through the zero crossings, spatial temperature information can be extracted from a single received waveform leading to tomographic reconstruction using only 2 pins.

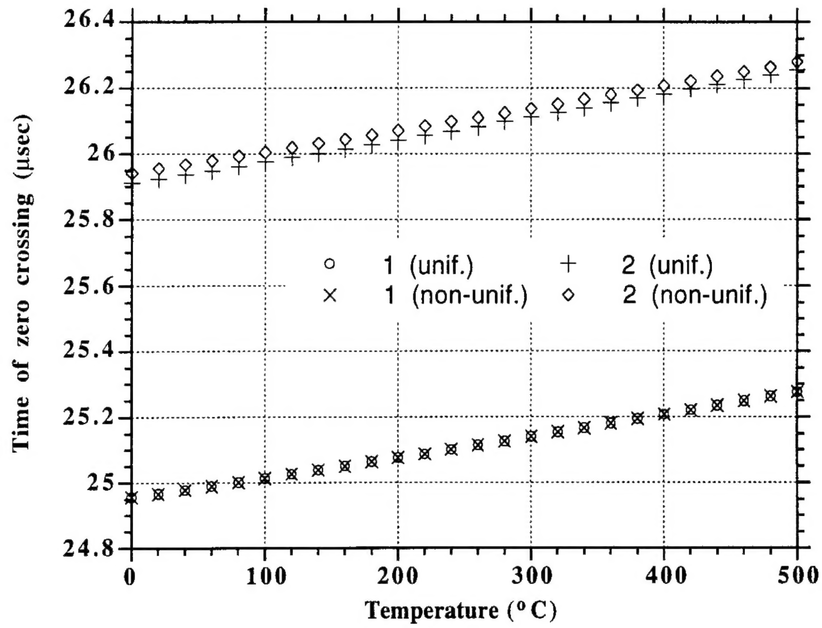

Figure 10. Calculated time of zero crossing variation for two different temperature distributions on the wafer. Half of the wafer is assumed to be 50°C above the indicated temperature in the nonuniform case.

CONCLUSION

Ultrasonic thermometry is used to measure in-situ wafer temperature in semiconductor processing. The method is capable of measuring average wafer temperature in 20-1000°C range with ±1°C accuracy with 20 Hz data rate. The technique is easily integrated to the current semiconductor processing chambers. It is insensitive to the process environment since the acoustic energy is confined to the wafer. The effect of finite wafer geometry is modeled and compared with experiments. Sensitivity variations with thin films are also considered theoretically and, in case of films of in the order of 100 Angstroms, it is calculated to be negligible. Temperature tomography, developed based on the same technique, is used to calculate the temperature distribution on the wafer with an estimated accuracy of ±5°C with an achievable data rate of 2 images/sec with parallel processing. The possibility of tomography with 2 pins is investigated by analyzing the spatial temperature information contained in a single received waveform.

REFERENCES

1. L. Peters, *Semiconductor International*, 8, pp. 56-62 (1991).
2. B. Peuse and A. Rosekrans, " In-situ temperature control for RTP via thermal expansion measurement", *Proceedings of 1992 MRS Spring Meeting.*
3. H. J. Skimmin, " Measurement of elastic constants at low temperatures by means of ultrasonic waves- data for silicon and germanium single crystals, and for fused silica", *J. Appl. Phys.*, 24 (8), pp. 988-997.
4. A. M. B. Braga, "Wave propagation in anisotropic layered composites", Ph. D. Thesis, Stanford University.
5. H. Simmons and G. Wang, Single crystal elastic constants and calculated aggregate properties - A handbook, MIT Press, 1971.
6. Y. Censor, "Finite series-expansion reconstruction methods", *Proceedings of IEEE*, 71, March 1983, pp. 409-419.
7. P. P. Apte and K. C. Saraswat, " Rapid thermal processing uniformity using multivariable control of a cicularly symmetric 3 zone lamp", *IEEE Trans. Semicond. Manifacturing*, 5, 180, 1992.